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Photolithography Process Characterization and 3D Simulation Using Track-mounted Development Rate Monitor Data

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Abstract

A track-mounted, in-situ Dissolution Rate Monitor (*DRM*) is used to study the impact of exposure variations on g-line, i-line and DUV positive chemically-amplified resists. In the i-line case, a comparative study between constant spray and a spray/puddle process was undertaken. In all cases, modeling parameters were extracted from the track-mounted DRM data and entered into 2D and 3D simulators using an experimentally-generated Development Rate vs. PAC concentration table. Simulated profiles were compared with actual SEM cross-sections. Whenever possible, DRM traces were used to analyze standing waves, surface inhibition effects and quantify resist performance by calculating contrast. For the g-line case, the impact of PEB temperature upon the standing wave effects, as quantified by the in-situ DRM data, was studied.

Introduction

As the lithographic world moves to reduced device feature sizes, one is confronted with reduced process latitudes. There is a need for exploring methods which will further optimize processes to achieve the best performance and stability. The harsh reality of increased complexity, coupled with the high cost of experimentation, underscores the increasing need for effective lithographic simulation. In recent years, a number of simulators have become readily available. Examples of these are two-dimensional simulators such as PROLITH/2™ and DEPICT™, and three-dimensional SAMPLE-3D™ and SOLID-C™. Unfortunately, most of these simulations are performed using aerial image techniques. Aerial imaging makes very little use of parameters extracted from real-time measurements. Consequently, inaccuracies have resulted.

Development is an extremely critical step in processing photoresist. Historically, most simulators assume an idealized threshold development model for all resists [1,2]. Due to the lack of accurate development modeling parameters, this assumption regularly condemns the simulation to a less-than-accurate conclusion. To avoid this pitfall, one may depend on resist manufacturers for these parameters or one may use the Perkin Elmer

Development Rate Monitor (*PE-DRM*). The PE-DRM is based upon an immersion development process. But again, most present day development processes are *track-based* (e.g. *puddle and spray/puddle techniques*) not immersion. Due to design limitations, the PE-DRM is unable to measure *in-situ* photoresist dissolution rates for track-based, puddle and spray/puddle processes. Consequently, development rate data extracted using the PE-DRM are not very useful for realistic simulation of advanced, track-based development techniques. This has lead to the investigating the use of a track-mounted DRM [14].

This paper focuses on experiments designed to demonstrate the effectiveness of photoresist characterization and modeling based upon dissolution rate monitoring using a track-mounted, in-situ development rate monitor (DRM). The DRM used was the LITHACON™ system, developed by SITE Services, Inc. The LITHACON system is a multi-wavelength, interferometric tool which uses eight wavelengths (ranging from 700 - 960 nm) to collect dissolution data in-situ. Its high sampling rates (up to 40 samples per second) provided a unique opportunity to observe minute variations in the development process. The LITHACON tool's multiple-wavelength capability, coupled with its use of circularly polarized light, enabled us to collect data through adverse process conditions, even through the notorious "red cloud" created during the dissolution of many positive resists [15, 16].

In the following study, three types of positive photoresist were examined -- g-line, i-line and DUV chemically-amplified resists. Their respective dissolution characteristics, as a response to variation of exposure energies, were studied. In each case, development rate was measured as a function of the film depth [9]. The packages LITHACON™ and XTRAK™ software were used to automatically extract development rate as a function of PAC concentration in the form of a table. Exposure energies were varied between sub E_0 to well above the nominal dose to allow extraction of development rates for a wide range of PAC concentration. The resulting table contained quantitative resist modeling parameters ready for input into 3D and 2D lithography simulators such as SOLID-C and PROLITH/2.

In the case of the i-line resist, a comparative study was made for a spray and a spray/puddle process. For the g-line resist, the influence of different PEB temperatures on reducing standing wave effect was studied [1].

Experimental Procedure

The experimental resist processes used an array of open frame exposures for i-line and DUV resists. For g-line, an exposure test mask was used. It consisted of lines and spaces, in varying dimensions, ranging from 0.6 to 10 μm . The LITHACON system was mounted above the develop cup at a height of around four-to-six inches. (See Figures 1 and 2 for a block diagram of a typical setup.)

The following experimental conditions were used for evaluating the in-situ development rate information.

For g-line resist:

Track:	GCA 1006 Wafertrac®
Prime:	HMDS vapor
Substrates:	100 mm bare silicon wafers
Dehydration bake:	250° C for 90 seconds
Softbake:	100° C for 45 seconds
Resist Used:	Shipley 812
Film thickness:	1.2 μm
Exposure tool:	GCA 6800 DSW g-line stepper, 0.5 NA
Exposure energy :	Varied between 75 mj/cm^2 to 255 mj/cm^2
Post Exposure bake:	115° C for 60 seconds using hard contact
Developer type:	MF 321 at 0.21N
Development time:	Adjusted for each exposure to ensure resist clearing
Development method:	Single puddle

For i-line resist:

Prime:	Used recommended conditions supplied by resist vendor
Substrates:	150 mm bare silicon wafers
Softbake:	Used recommended conditions supplied by resist vendor
Resist Used:	i-line resist
Film thickness:	1.2 μm
Exposure tool:	NA - 0.54, $\sigma = 0.52$
Exposure energy :	Varied between 54 mj/cm^2 and 500 mj/cm^2
Post Exposure bake:	Used recommended conditions supplied by resist vendor
Developer type:	Used recommended conditions supplied by resist vendor
Development time:	Adjusted for each exposure to ensure resist clearing
Development method:	Constant spray and spray/puddle

For DUV resist:

Prime:	HMDS vapor
Substrates:	150 mm bare silicon wafers
Dehydration bake:	150° C for 90 seconds
Softbake:	100° C for 60 seconds
Resist Used:	APEX-E
Film thickness:	0.78 μm
Exposure tool:	Nikon 1505 EX1 DUV stepper, 0.42 NA, $\sigma = 0.5$
Exposure energy :	Varied between 2.0 mj/cm^2 to 8 mj/cm^2
Post Exposure bake:	90° C for 90 seconds using direct contact
Developer:	OCG HPRD 441 at 0.23N
Development time:	Adjusted for each exposure to ensure resist clearing
Development method:	Single puddle

Results and Discussion

Data collected from the in-situ DRM was used to characterize and model spray/puddle, constant spray and stream/puddle lithographic development processes for all three resist types. Whenever possible, a table was compiled containing Development Rate vs. PAC concentration information using the aforementioned SITE-developed tools (*namely the LITHACON system for development rate calculations and XTRAK software for PAC concentration calculations*). This tabular data was then entered into a 3D photolithographic process simulator. A high degree of agreement between the experimental and simulated data prompted our use of the SOLID-C simulator [13].

During the course of experimentation, a comparative study between the dissolution properties of the i-line spray and spray/puddle process was undertaken. Signals were collected over a wide range of exposure energies ranging from 54 mJ/cm^2 to 500 mJ/cm^2 where the nominal exposure was 200 mJ/cm^2 . This range was undertaken to ensure data was collected for regions well below E_0 to well above nominal. A family of Thickness vs. Time graphs for the various exposure doses was generated. This information was used to generate the characteristic curve which illustrates contrast and E_0 information as seen in Figures 3-8.

While examining development rate information for the i-line case, it was noticed a constant spray development process had a higher development rate than a spray/puddle process. The Development Rate vs. Exposure information for the spray and spray/puddle process is displayed in Figure 9. The Development Rate vs. PAC table was generated using the strategy described in Figure 1. A graphical illustration of Development Rate vs. PAC concentration is shown in Figure 10. This information was used for profile simulation instead of the predefined development models [3-4, 6-8]. For each case, the average development rate was calculated in the bulk region corresponding to regions between 35% and 60% of the resist depth. The comparison between the simulated and measured SEM profiles are illustrated in Figures 25-30.

For the DUV chemically-amplified resist APEX-E, data were collected for energies ranging from 2 mJ/cm^2 to 8 mJ/cm^2 where the nominal dose was 6 mJ/cm^2 using a stream/puddle process. Graphs illustrating Development Rate vs. Exposure, Thickness vs. Time for a range of exposure doses, and the characteristic curve displaying the contrast and E_0 information are shown in Figures 11-14.

Also noted was an exposure-dependent thickness loss for APEX-E during the PEB step. These data were measured using the PROMETRIXTM film thickness measurement tool. (*See Figure 15.*) The refractive index was assumed to remain unchanged during the PEB step. This may be an invalid assumption. However, the thickness loss information was vital for correct development rate calculation by the LITHACON system since the tool requires initial resist thickness information.

The LITHACON system collected data over a range of eight wavelengths and used these multiple wavelengths to optimize the primary signal and minimize red cloud effect rather than measure absolute film thickness.

The inability to account for the thickness variation at different exposures after the PEB step resulted in a significant error in calculations. The contrast curve using Prometrix-measured data was laid upon the LITHACON-calculated contrast curve at the time slice of 60 seconds (*the LITHACON system has the ability to generate contrast curves for any chosen time slice - see Figure 16*). Close agreement was noted. Finally, simulated profiles using SOLID-C are displayed and compared with SEM profiles as illustrated in Figures 31-32. Data entered into SOLID-C included a table of bulk Development rate vs. Exposure.

Unfortunately, in the case of g-line Shipley 812 resist, development rate data were not collected for a wide range of exposures. Low exposure doses took quite long to clear. By such time, bubbles (*which adversely affect data collection*) were noted. Therefore, data was collected only between 75 and 255 mJ/cm². Graphs illustrating the results are presented in Figures 17-19.

While analyzing the development rate information across the depth of the resist, an effort was undertaken to study the standing wave effects, if any, for each of the processes. In the i-line spray/puddle process described above, evidence of standing waves, even after the PEB step, was noted. (*See Figure 20.*) The result of laying the Development Rate vs. Depth graph generated by LITHACON upon the PAC vs. Depth graph generated by XTRAK, supported this conclusion for any given process condition.

The PAC vs. Depth curve was generated with a PEB diffusion length equal to zero. The graph displayed modulations which, in turn, indicated regions of high and low PAC concentration along the depth of the resist due to standing waves.

Development Rate vs. Depth information was collected for standard process conditions which included a PEB step. Regions along the resist depth with low PAC (*as illustrated by XTRAK*) had higher development rates and vice versa. This indicated, even in the standard process, there was continuing evidence of standing waves. Even so, the SEM profiles suggested *no* evidence of standing waves after the PEB. The reason for this behavior is unclear [5]. In the i-line resist case, the development rate information entered into the SOLID-C simulator was a bulk development rate averaged between 35% and 65% of resist depth. (*A feature allowing z-dependence for development rate data is currently being added to XTRAK. This feature will enhance the accuracy of simulation.*)

A mismatch in phase information was noted as resist depth increases. This may be attributed to changes in the refractive index along the depth of the resist. Further investigation into this phenomenon is warranted.

Similar analysis was conducted for the g-line resist. In this case, we varied the PEB temperatures. A reduction of standing waves with the increase in PEB temperature was clearly noted. Moreover, it was found that 110° C for PEB was probably closest to optimum since higher PEB temperatures reduced the development rate considerably. (See *Figure 21.*)

Data collection for the bulk of the resist was very clean for both the spray and the spray/puddle process. However, better information was available during the early part of the development process for the constant spray case. While analyzing the development rate vs. depth information for the various cases, a reduction in the development rate near the resist substrate interface was noticed. The cause of this phenomenon is not yet clear. However, it may be attributed to reduced development uniformity of the region under investigation. A visual illustration of this effect is displayed in Figures 22-24.

Conclusions

The results presented here show that effective process simulation for realistic spray/puddle combination processes can only be performed when using a track-mounted, in-situ DRM. Standing wave effects are not always eliminated even though SEMs may suggest they have been. Different resists show differing inhibition effects; a tool is required to quantify this effect. The data which illustrates development rate in varying PEB conditions, as collected by the in-situ DRM, are clearly useful. They show how the LITHACON and XTRAK tools can be used to optimize the PEB temperature for minimizing standing wave effects *without* the use of SEM responses. Moreover, these same tools can be used for the solvent removal process by analyzing the influence of PEB temperatures on the bulk development rate.

Future planned projects using the LITHACON and XTRAK combination include: quantifying inhibition depth for various delay times between exposure and PEB for chemically-amplified resists, measurement of the dynamic change in the refractive index, and measurement of PEB diffusion lengths in various PEB conditions for DNQ/Novolak resists (*during lithography*) using DRM data.

Acknowledgments

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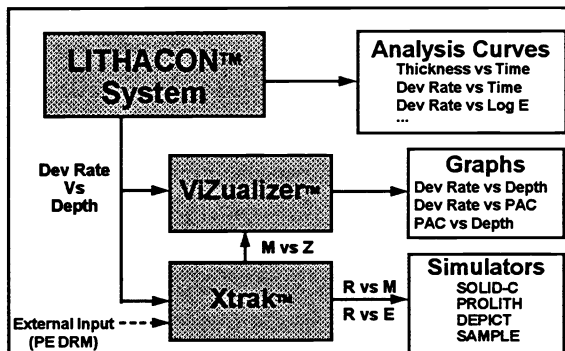


Figure 1. Functional Block Diagram

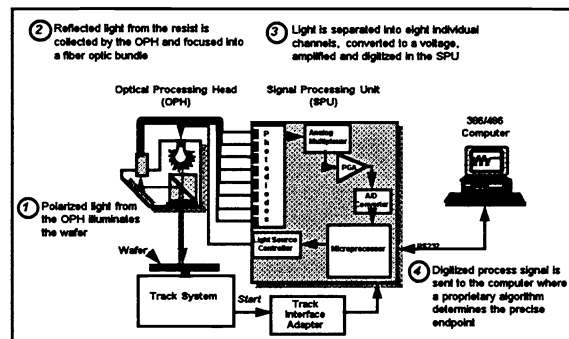


Figure 2. Lithacon Hardware Description

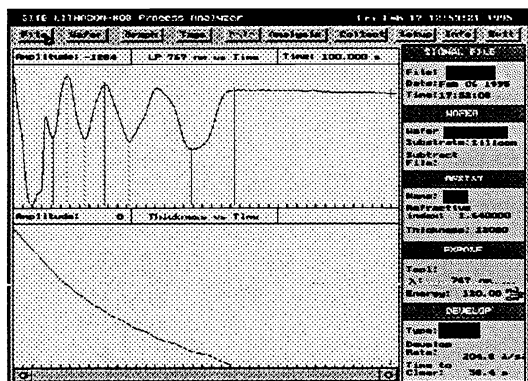


Figure 3. Typical Signal: i-line Resist - Puddle Develop

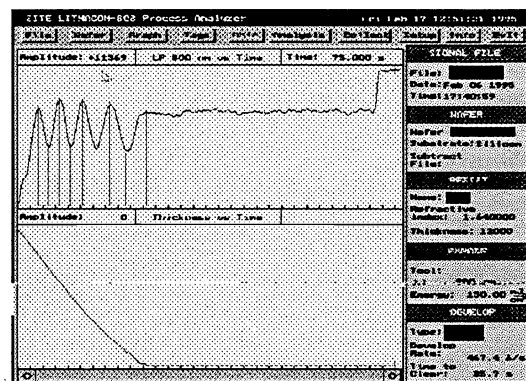


Figure 4. Typical Signal: i-line Resist - Spray Develop

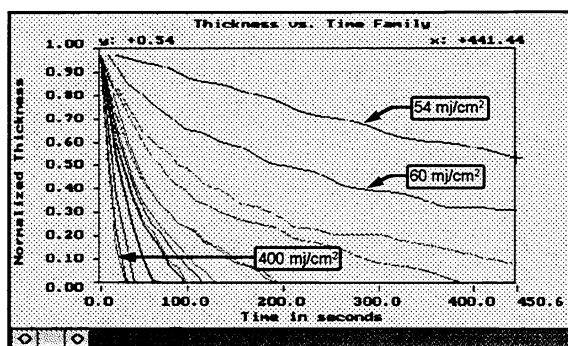


Figure 5. Thickness vs Time Family: i-line Resist - Puddle Develop

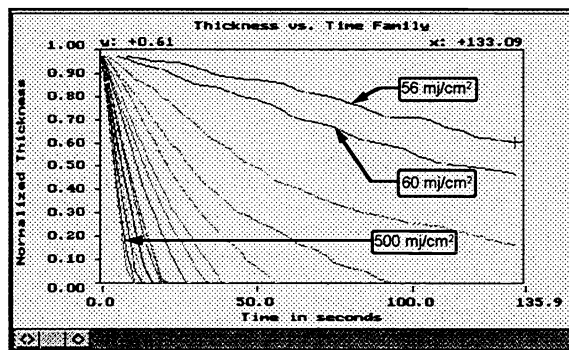


Figure 6. Thickness vs Time Family: i-line Resist - Spray Develop

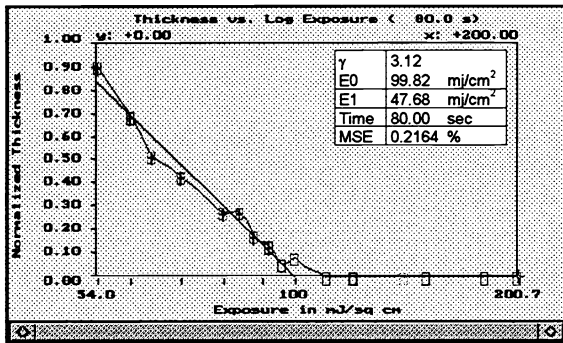


Figure 7. Contrast Curve: i-line Resist - Puddle Develop

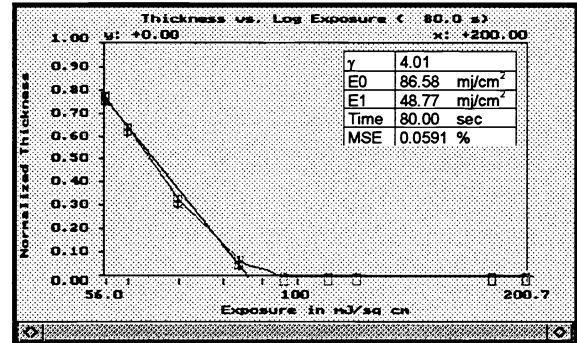


Figure 8. Contrast Curve: i-line Resist - Spray Develop

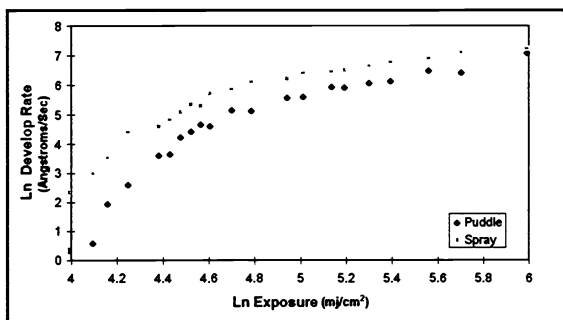


Figure 9. Develop Rate vs Exposure: i-line Spray and Puddle Processes

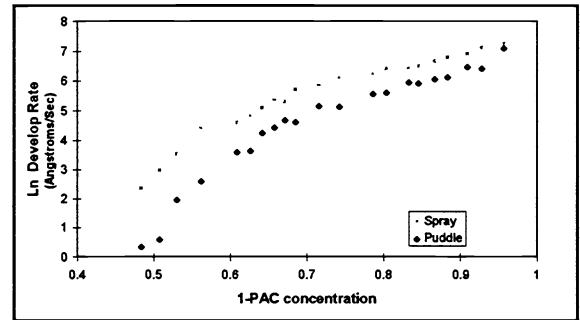


Figure 10. Develop Rate vs PAC Concentration: i-line Spray and Puddle Processes

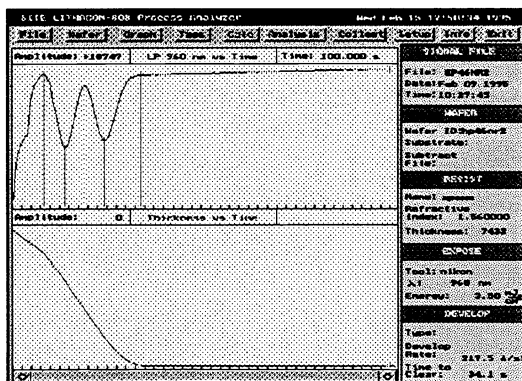


Figure 11. Typical Signal: Apex-e Resist

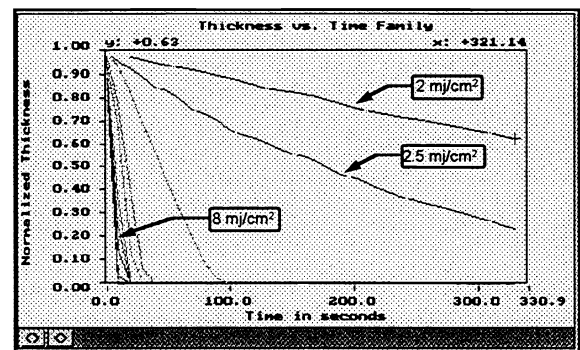


Figure 12: Thickness vs Time Family: Apex-e Resist

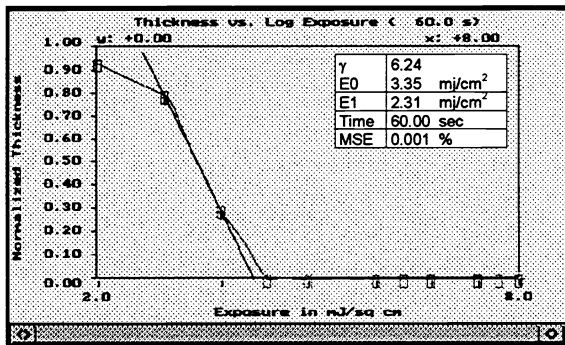


Figure 13: Contrast Curve: Apex-e

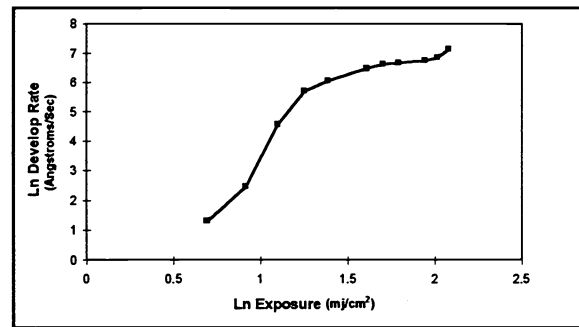


Figure 14: Average Develop Rate vs Exposure: DUV Stream/Puddle Process

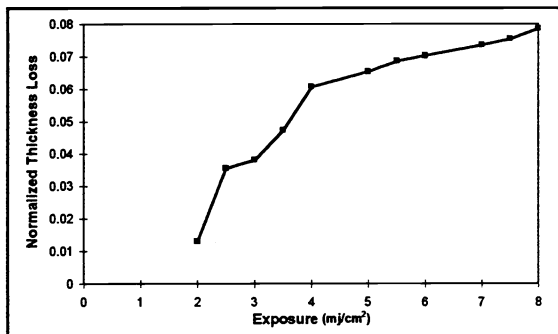


Figure 15: Thickness Loss during PEB: DUV Resist

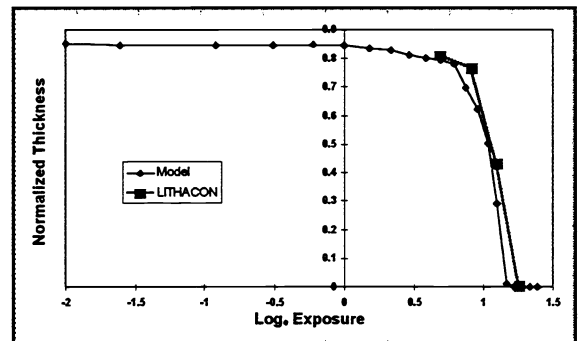


Figure 16: LITHACON vs Prometrix Contrast Curve: Apex-e Resist

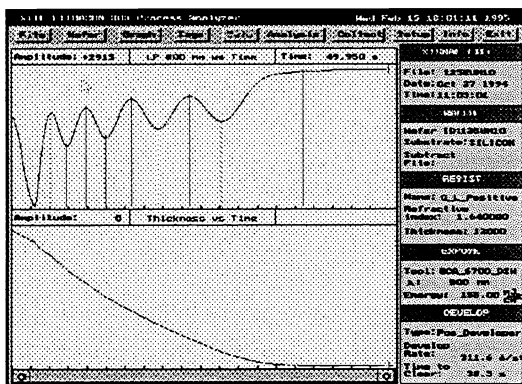


Figure 17: Typical Signal: g-line Resist

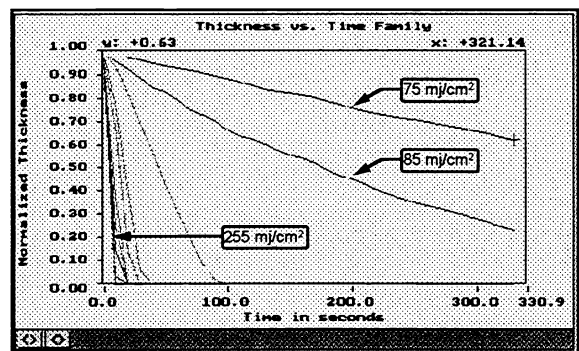


Figure 18: Thickness vs Time Family: g-line Resist

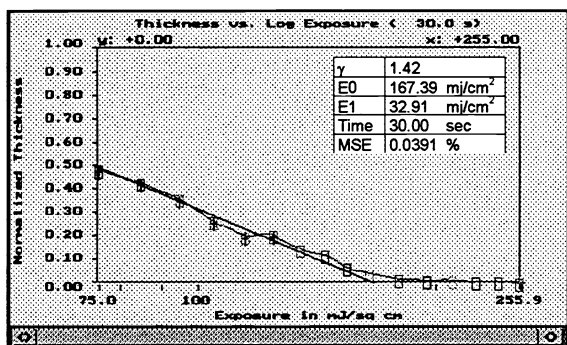


Figure 19. Contrast Curve: g-line Resist

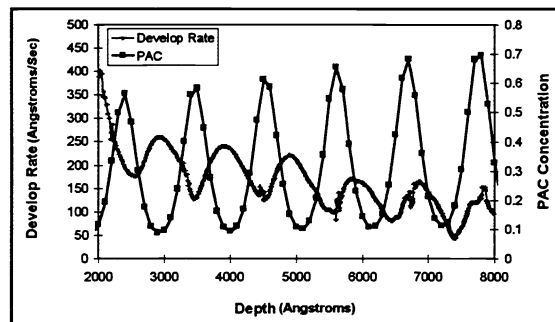


Figure 20. Develop Rate vs PAC Concentration: i-line Resist, Exposure = 96mJ/cm²

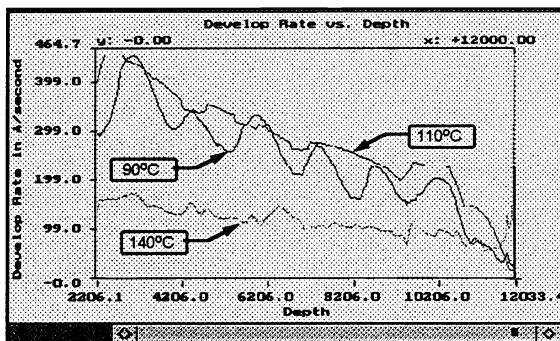


Figure 21. Effect of PEB Temperature on Develop Rate using Develop Rate vs Depth Data

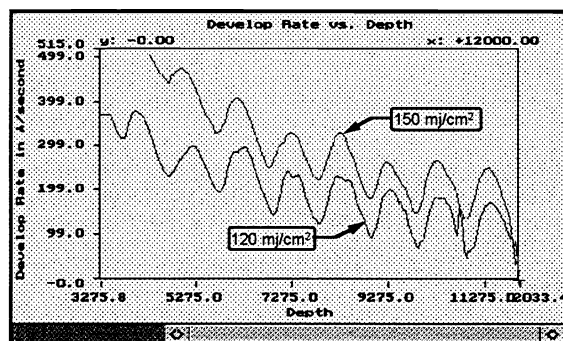


Figure 22. Develop Rate vs Depth: i-line Resist - Puddle Develop

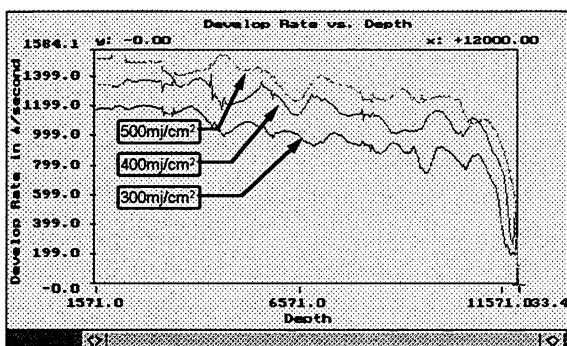


Figure 23. Develop Rate vs Depth: i-line Resist - Spray Develop

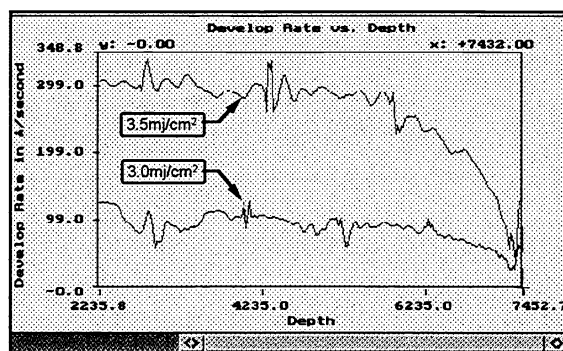


Figure 24. Develop Rate vs Depth: Apex-e

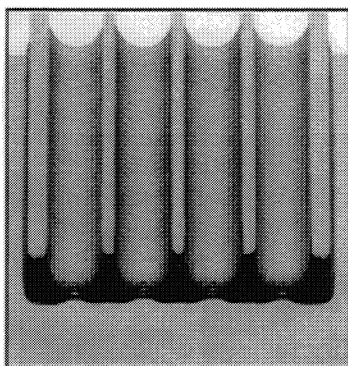


Figure 25. Focal Position = 1.0
Simulation Window: (-2.500/-2.500)
(2.500/2.500) SOLID-C™

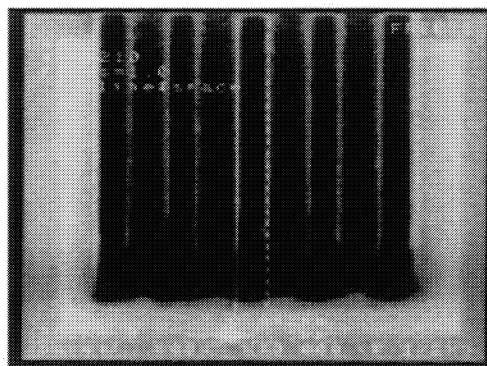


Figure 26. Focal Position = 1.0 (SEM)

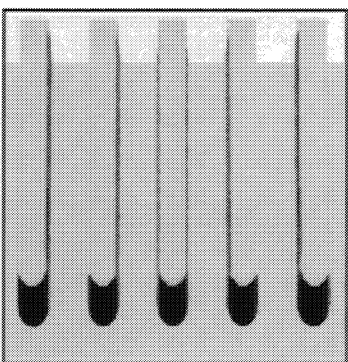


Figure 27. Focal Position = 0.0
Simulation Window: (-2.500/-2.600)
(2.500/2.600) SOLID-C™

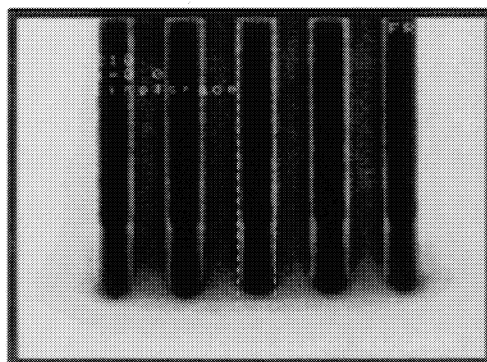


Figure 28. Focal Position = 0.0 (SEM)

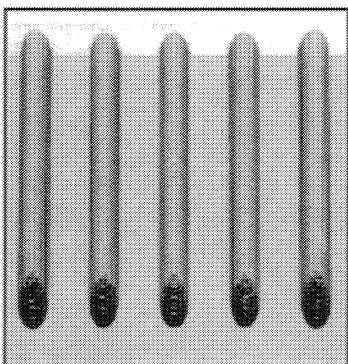


Figure 29. Focal Position = -1.4
Simulation Window: (-2.500/-2.600)
(2.500/2.600) SOLID-C™

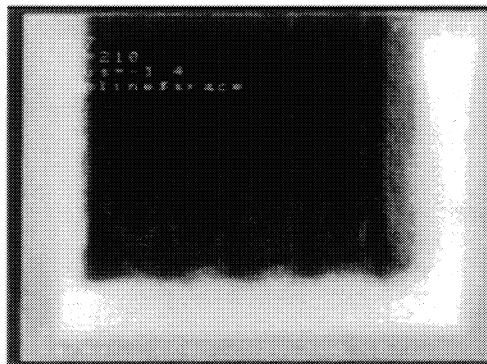


Figure 30. Focal Position = -1.4 (SEM)

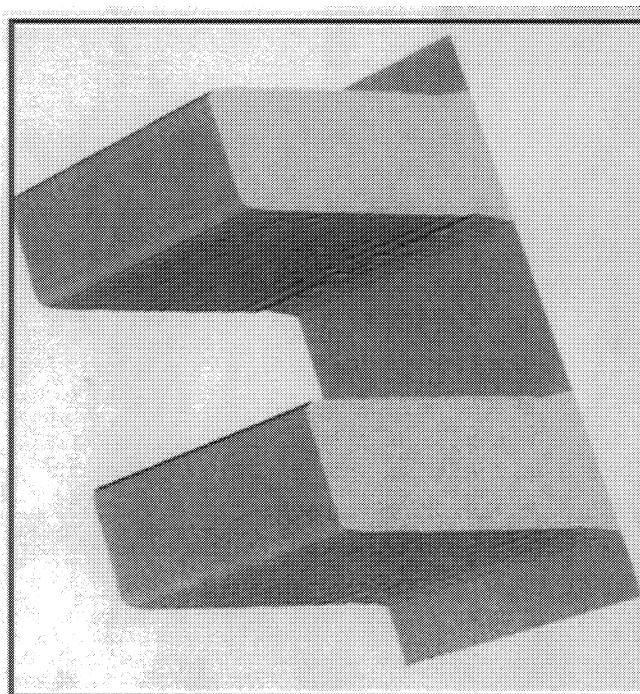


Figure 31: APEX-E SIMULATION (0.6 μm)
 Simulation Window: (-1.100/-0.500) (1.100/0.500)
 SOLID-C™

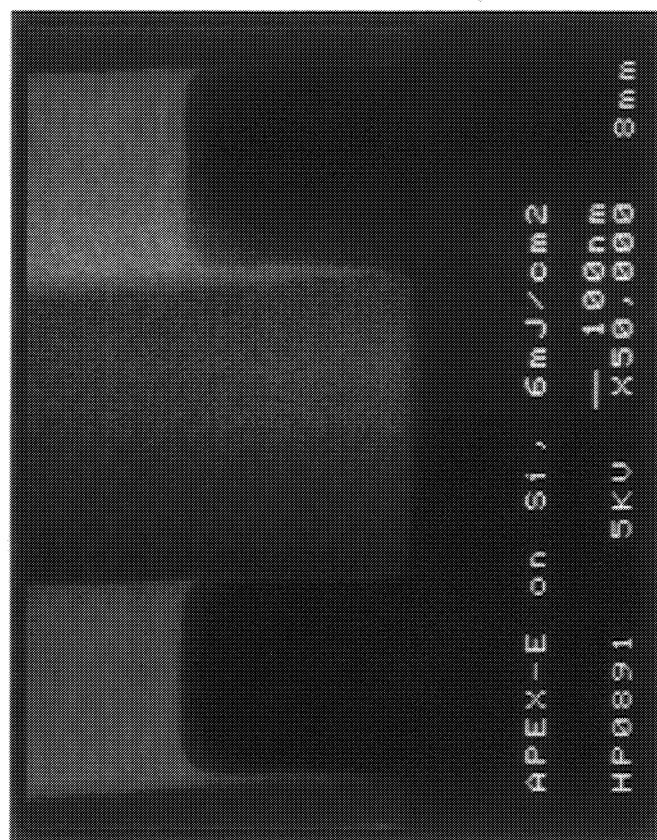


Figure 32: APEX-E SEM (0.6 μm)